DEVELOPMENT, PRODUCTION AND TESTS OF PROTOTYPE SUPERCONDUCTING CAVITIES FOR THE HIGH BETA SECTION OF THE ISAC-II HEAVY ION ACCELERATOR AT TRIUMF

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Abstract

The medium beta section of the ISAC-II heavy ion superconducting linear accelerator, consisting of 20 cavities, has been in operation at TRIUMF since 2006. The high beta section of the accelerator, consisting of an additional twenty cavities, is currently under development and is scheduled for completion in 2009. The cavity is a superconducting bulk Niobium two-gap quarter-wave resonator for frequency 141 MHz, optimum β_o=0.11, providing, as a design goal, a voltage gain of V_a=1.08 MV at 7 W power dissipation. The inner conductor is equipped with a donut drift tube. The cavity has a double wall mechanical structure with liquid Helium inside. Two prototype cavities for the ISAC-II high beta section were developed at TRIUMF and produced by a Canadian company, PAVAC Industries of Richmond, B.C. The prototypes are equipped with a mechanical dissipator to damp detuning environmental mechanical vibrations. An inductive coupler, developed at TRIUMF, provides low power dissipations to the liquid helium system. Superconducting RF tests of both cavity prototypes show that we have achieved the required frequency and exceeded the design goal parameters. Response of the cavity to liquid helium pressure fluctuations, Lorenz force detuning and microphonic sensitivity with and without the damper was tested. RF design, prototype production details and cavity test results will be presented and discussed.

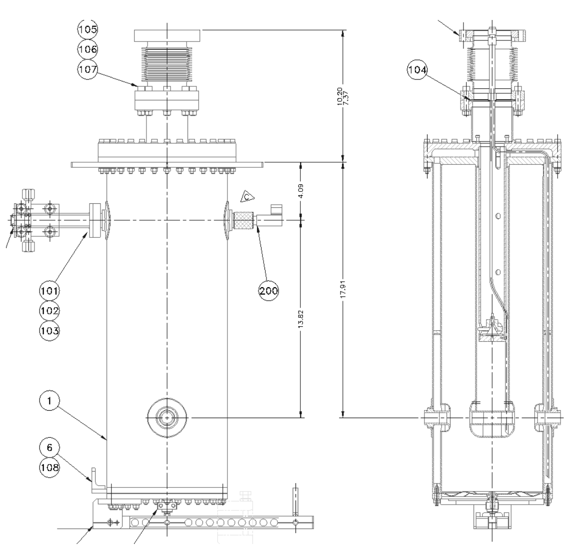


Fig.1. ISAC-II high beta cavity design.

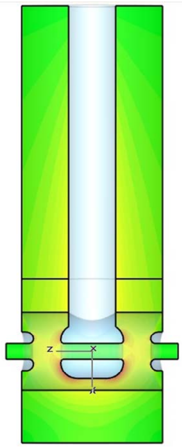
INTRODUCTION

The high beta section is supposed to double the energy of the ISAC-II superconducting accelerator by means of an additional twenty cavities [1]. These cavities will be housed in three cryomodules with common isolation and cavity vacuum. Two cryomodules will contain six cavities and the last one will contain eight cavities. The plan is to install the completed and tested cryomodules during an extended shutdown of ISAC-II starting in September 2009. The medium beta section is in operation since April 2006 and is reliable at an average acceleration gradient of 7 MV/m at 7 W power dissipation for helium, corresponding to peak electric and magnetic fields of 35 MV/m and 70 mT [2]. The medium beta design was accepted as a basis for the design of the high beta section.

CAVITY DESIGN

The design of the new ISAC-II superconducting high beta cavity is presented in Fig.1 and it is similar to the medium beta 106 MHz cavities design [3]. The operational frequency is 141.44 MHz and β_o=0.11. It is a bulk niobium double wall structure ~25% shorter than the medium beta cavity. The main difference is the donut shape of inner drift tube to provide higher particle velocity and better field symmetry. The acceleration gap is reduced from 40 to 35 mm and the grounded beam ports diameter is also reduced from 60 to 50 mm to maintain the 115 mm gap to gap distance in the same 180/60 mm coaxial arrangement. The shortened gap also favours an increased transit time factor. The position of RF ports was optimized for coupler operation. A mechanical dissipator is inserted inside of the inner conductor of the cavity to dampen vibrations. The bottom plate of the cavity is modulated and slotted to provide a deformation of at least ±3 mm for cavity tuning. The inductive input coupler is equipped with a heat sink for the liquid nitrogen cooling and ceramic (Shapal-M) support to provide low load for the helium system and stable operation at a forward RF power ~200W in overcoupled regime. The capacitive pickup housing is equipped with a special nozzle for gas nitrogen flow which should create overpressure in the cavity during cryomodule assembling and in such a way prevent contamination.

CST 2008 Microwave Studio model and cavity parameters are shown on Fig.2. Virtual volumes in the model were used to in the simulation to avoid errors from meshing. The models include a virtual cylinder around the



f	MHz	141.44
aperture	mm	20
gap	mm	35
drift	mm	80
Outer dia	mm	180
Inner dia	mm	60
Height	mm	560
bo		0.112
TTFo		0.936
U/Ea^2	J/(MV/m)^2	0.067
RsQo	Ohm	26
Ep/Ea		4.9
Bp/Ea	mT/(MV/m)	10
Bc/Ea	mT/(MV/m)	0.1
Df/Dx	kHz/mm	
beam ports		120
top		-268
bottom		10

Fig.2. CST model and cavity RF parameters

beam tube donut and a virtual coaxial in the high magnetic field stem region. The peak electric field is calculated from a donut geometry parameterization. Bp is calculated assuming a cosine longitudinal, hyperbolic radial magnetic field distribution in the virtual coaxial and the value of magnetic field stored in this volume. Frequency sensitivity for beam ports and top and bottom flange displacements are calculated from surface densities of electric and magnetic fields by using the Slater theorem.

The acceleration gradient definition is

$$E_a = V_a / D \quad (1)$$

where Va is an acceleration voltage gain of the cavity at optimum velocity βo (including a transit time factor TTFo), D is a conventional cavity length chosen as the cavity volume diameter. The design goal is conservative, Ea=6 MV/m, and corresponds to Va=1.08 MV. The steering effect due to the electric and magnetic transverse rf fields can be largely compensated by shifting the cavity 1.3 mm downward relatively to the optical axis.

The bottom tuning plate is removable for easy cavity access with a metal to metal contact. The tuning plate position is optimized to have sufficient frequency sensitivity, ~10 Hz/mm, while maintaining an acceptably low magnetic field ratio Bc/Ea<0.1 mT/(MV/m) in the bottom tuning plate to flange non-welded contact.

PRODUCTION

Two copper dummy cavities were produced at PAVAC Industries for niobium prototypes production preparation and training purposes. This modelling period was useful in developing forming and welding fixtures and to develop frequency tuning steps. The estimate of frequency shift from room temperature to cold temperature was done based on previous experience with the medium beta ISAC-II cavities and ALPI cavities of INFN-LNL. To a good approximation the frequency shift is proportional to operational frequency: 156 kHz for 80 MHz ALPI cavities and 190 kHz for 106 MHz ISAC-II medium beta cavities. Following this scaling we predicted a 253 kHz frequency shift. Later on we found that it is just 4.5% less than actual the actual shift of 264 kHz.

Frequency goals and tuning procedures during production were defined based on the data from the copper dummy cavities production, frequency sensitivities from CST cavity model and niobium welding trials. The sequence of tuning operations for the cavity production is the following:

- Cavity length trim before flanges welding; at top sensitivity -268 kHz/mm (data on Fig.2)
- Acceleration gap adjustment before the beam ports welding; beam ports sensitivity 120 kHz/mm assuming movement at both gaps
- Final cut of bottom flange after all welds; actual sensitivity is ~8 kHz/mm

BCP etching of parts was done at TRIUMF chemical laboratory to achieve high quality of electron beam welding. After all welds, tunings and pressure tests the cavities were BCP etched ~80 μm and high pressure rinsed with deionised water to provide a high purity of the surface.

CAVITY TESTS

For cavity tests the TRIUMF ISAC-II single cavity cryostat was used and the data are presented in Table 1. The cavity is assembled and equipped with dissipator, coupler, tuning plate, pickup, temperature sensors and enclosed in mu-metal shield. The cavity is pumped then baked for two days achieve a temperature of 360K C at a vacuum of 10^{-6}Torr. This is followed by two days of radiative cooling with LN2 in the thermal shields to reach 200K before filling the cryostat with liquid helium. The resonant frequency of the superconducting cavities is within +/-17 kHz of the goal operational frequency 141.44 MHz within the range of compensation allowed by small deformations of the tuning plate.

Table 1: Prototype Cavities Test Results

Cavity	#	3	4
fo	MHz	141.423	141.456
Qo		1.10E+09	1.20E+09
Ea@7W	MV/m	8.1	8.8
EaMax	MV/m	10.9	12.5
Df/Dp	Hz/Torr	-3.3	-1.7
Df/DEa^2	Hz/(MV/m)^2	-0.8	-0.9
Df300-4K	kHz	263	265

RF conditioning of the cavity indicated the 1^{st} level of multipactor at Ea~10 kV/m, which according to Frequency-Gap Product in Two Surface Multipactor model [4], corresponds to the 1^{st} order of the acceleration gaps. There are also some several higher levels. The multipactor levels process out in several hours using pulsed rf conditioning at strong coupling. Both prototypes exhibited strong field emission at ~5 MV/m that could be eventually conditioned out by repeated conditioning. RF conditioning pulses varied from t~0.2-0.5 s and T~1 s at forward power 200-400 W with sufficient overcoupling to achieve fast cavity response with sufficient field level. For higher efficiency of rf conditioning helium conditioning at ~10^{-5}Torr was also employed. The calibration of the pickup voltage for acceleration gradient Ea is calculated from the decay time constant and power dissipation during critically coupled cavity measurements.

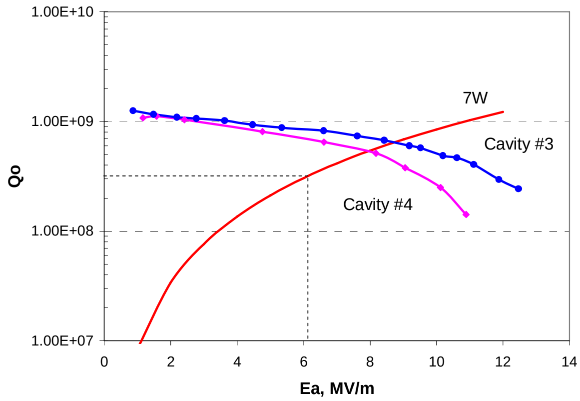


Fig.3. RF characterization results for prototype cavities

The resulting Q-curves after conditioning of the prototype cavity cold tests are presented in Fig. 4. A maximum acceleration gradient for one prototype of Ea>12 MV/m is achieved, which corresponds to Ep>60 MV/m and Bp>120 mT. The limitation is from radiation levels produced in the test area. At 7W power dissipation the cavities acceleration field Ea~8.5 MV/m is significantly exceeding the design goal of 6 MV/m. The measured quality factor Qo=1.1-1.2*10^9 corresponds to a residual resistance of ~15 nΩ.
The sensitivity for slow helium pressure variation is 3 Hz/Torr. Lorenz force detuning is ~-0.9 Hz/$(MV/m)^2$.

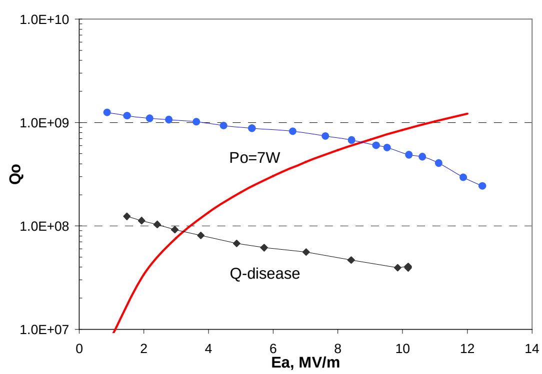


Fig.4. Cavity#4 with and without Q-disease

A Q-disease test has been done for one of the cavities. The cavity was kept in the range 50-150K for several days due to a cryogenic problem. The Q-curve taken after this is shown in Fig.4. The quality factor drops an order of magnitude and the Q-curve shape becomes concave upward, a characteristic of Q-disease. In the test the field is limited by high helium boiling only. After thermal cycling up to room temperature the Q-disease disappears.

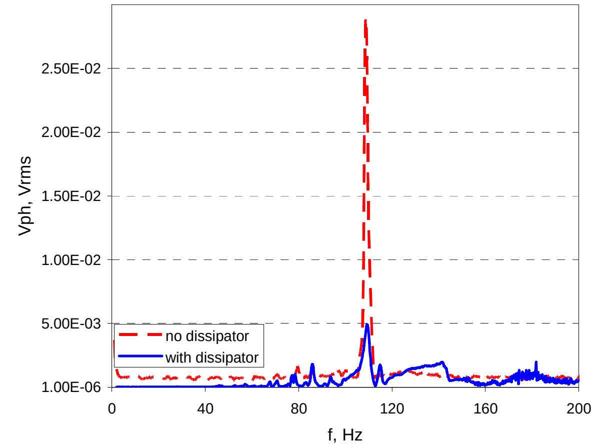


Fig.5. Phase noise without and with dissipator

The cavity lowest mechanical resonance frequency ~110 Hz is calculated and measured. Vibration measurements are taken with and without a mechanical dissipater in position. The peak phase error signal after a calibrated cavity excitation for the two cases is shown in Fig. 5. In such a way the dissipator can help reduce the forward power (reduce the over-coupling) required to provide a stable bandwidth for cavity operation.
Several ancillary tests have also been completed. 1) The LN2 cooled coupling loop produces <0.3 W power dissipation in helium system at 200 W forward power, 2) a new tuner system was tested with 0.04 Hz/step resolution, velocity 74 Hz/sec and tuning window of 18 kHz. In locked phase loop it shows good compensation of helium pressure variation, 3) the solid state amplifier prototype, developed in QEI Corporation shows very good performance in reducing phase noise in comparison with a tube amplifier.

CONCLUSIONS

Two superconducting bulk niobium ISAC-II high beta prototype cavities have been developed, produced and successfully tested. The acceleration gradient at nominal power dissipation 7W is more than 8 MV/m. The fabrication of twenty cavities are underway with the first six expected in October 2008.

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